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Relationship between surface velocity divergence and gas transfer in open-channel flows with submerged simulated vegetation

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Abstract. Velocity and gas concentration measurements were carried out to reveal gas transfer phenomena in open-channel turbulent flows with flat bottom and submerged vegetation bottom conditions. A large-scale coherent vortex appears near the vegetation top due to shear instability, and the submerged vegetation was found to promote gas transfer beneath the air-water interface. Furthermore, we revealed a great dependency of gas transfer on vegetation density. The present measurement results propose a new surface divergence model with wide generality, connecting reasonably the gas transfer velocity and the surface divergence intensity in open-channel flows, irrespective of bottom roughness conditions.

1. Introduction

Surface velocity divergence is closely related to coherent motions induced by bottom turbulence. Instantaneous upward and downward motions occur together with the strong surface divergence, and it results in periodic renewal of the dissolved gas situation in the free surface. The surface velocity divergence plays a significant role in the gas transfer rate as pointed out by McCready *et al.* (1986), which introduces a theoretical relation, i.e., a surface divergence model (SD model).

It is generally well known that natural rivers are composed of various bottom roughness features such as submerged vegetation, gravel, sand waves, etc. They contribute to produce greater turbulence compared with flat bottom conditions. Practical prediction methods of the gas transfer rate are modelled by friction velocity. However, the friction velocity is hard to evaluate accurately in natural rivers. With development of video recording devices and particle image velocimetry (PIV) techniques, the horizontal velocity components could be obtained in the free surface, and it is possible that the SD model will be the most useful method to predict the gas transfer rate in rivers.

The present study focuses on the development of an SD-based model for open-channel flows with submerged plants. Surface divergence is found to be affected significantly by the free surface velocity. In the vegetated-bed cases, the divergence intensity is greater because of the shear vortex produced at the vegetation edge than the flat bottom condition. We propose a new practical model considering the turbulence dynamics. A proportionality coefficient of the original SD model depends on the water depth, and thus, a modified SD model was required that can consider the effects of water depth on gas transfer. We examined whether the free surface streamwise velocity and turbulent kinetic energy can



be used as a proper velocity scale. In both cases of smooth and vegetated bed conditions, the modified SD model is proved to be useful without a dependency on the bulk mean velocity and depth.

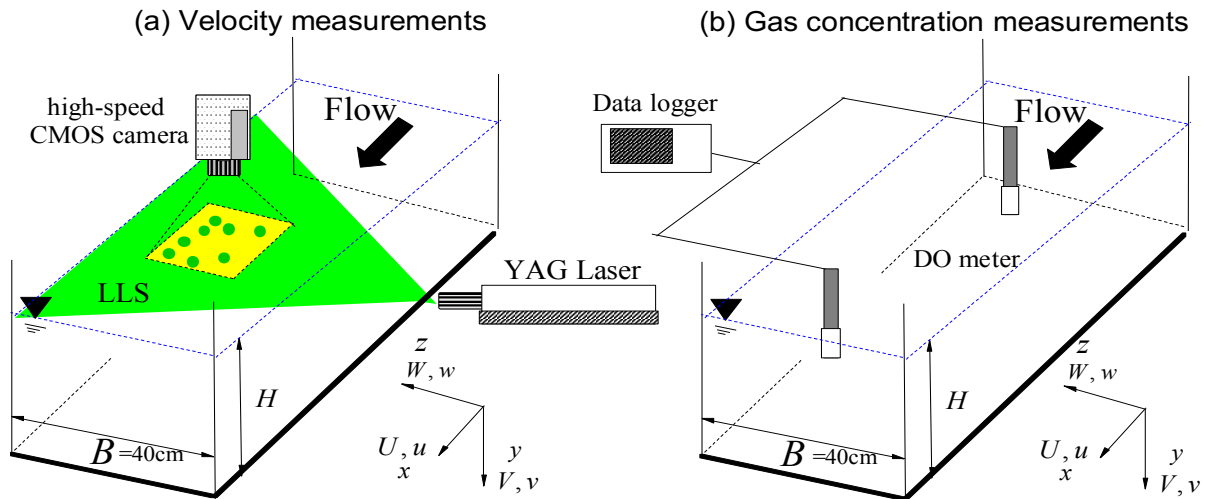


Figure 1. Experimental setup

2. Experimental procedure

Figure 1 shows a glass-sided water flume that is 16-m long, 40-cm wide, and 50-cm high, in which water current was generated by computer control and an electromagnetic flow meter. Streamwise, vertical and spanwise coordinates are x , y and z , respectively. The vertical origin, $y = 0$, was chosen as the free surface. The time-averaged velocity components in each direction are defined as U , V and W , and the corresponding turbulent fluctuations are u , v and w , respectively. The measured region was located at about 7 m downstream from the channel entrance, at which the turbulent flow was fully developed. A 2-W YAG laser (continuous wave) was used for the laser light sheet (LLS) as shown in figure 1a. The 2-mm thick LLS was projected horizontally in the surface elevation. The spatial resolution is about 0.22 mm per pixel. The LLS plane was illuminated together with tracer particles (diameter of 100 μm and density of 1.02 g/cm^3) and captured by a high-speed CMOS camera. The time variation of the instantaneous velocity vectors (\tilde{u} , \tilde{w}) was calculated by PIV algorithm (see Nezu and Sanjou 2011). The PIV analysis was conducted by direct correlation, in which the interrogation window size is 25×25 pixels. When the correlation value between the first and second image patterns is less than 0.4, a local velocity vector was judged an invalid vector, and an interpolated velocity value was given to the corresponding position using surrounding valid vectors.

Dissolved oxygen (DO) measurements were also conducted to evaluate directly the gas transfer velocity in the same manner as Moog *et al.* (1999). After calculation of the reaeration coefficient k_2 , the gas transfer velocity k_L could be obtained multiplying k_2 and H . These measured transfer velocity values were modified to those expected at 20°C water temperature. It is well known that advection effects should be considered in the streamwise distance when we calculate k_L in unidirectional flows such as an open-channel stream. In the present experiment, two DO meters were aligned in the streamwise direction with 7-m span as shown in figure 1b. These measured signals were transferred to the data logger every 1.0 s.

Table 1. Hydraulic conditions for flat bottom flows.

H (cm)	U_m (cm/s)	U_s (cm/s)	Re	Fr	$\tan\theta$
8	5.0	6.2	4000	0.056	$1/10^4$
8	10.0	12.3	8000	0.113	$1/10^4$
8	20.0	24.6	16000	0.226	$1/10^4$
8	30.0	35.1	24000	0.339	$3/10^4$
8	40.0	45.6	32000	0.452	$5/10^4$
6	5.0	6.4	3000	0.065	$1/10^4$
6	10.0	12.5	6000	0.130	$1/10^4$
6	20.0	24.3	12000	0.261	$2/10^4$
6	30.0	36.0	18000	0.391	$4/10^4$
6	40.0	47.8	24000	0.522	$6/10^4$
4	5.0	6.3	2000	0.080	$1/10^4$
4	10.0	12.3	4000	0.160	$1/10^4$
4	12.5	15.1	5000	0.200	$1/10^4$
4	15.0	18.0	6000	0.240	$1/10^4$

Table 2. Hydraulic conditions for flows with submerged vegetation on the bottom.

λ	H (cm)	U_m (cm/s)	U_s (cm/s)	Re	Fr	$\tan\theta$
0	15	10.0	12.0	15000	0.082	$1/10^4$
0.0236	15	10.0	15.7	15000	0.082	
0.0947	15	10.0	16.8	15000	0.082	
0.3789	15	10.0	19.0	15000	0.082	

Table 1 shows hydraulic conditions, in which U_m is bulk-mean velocity and U_s is time-averaged free-surface streamwise velocity in the centerline of the flume. Subscript s means the free surface. Fr and Re are Froude number and Reynolds number defined using U_s and H , respectively. The DO measurements take long durations, from 10 to 40 hours, and thus, we kept constant the water and air temperatures by air conditioners. All fifteen hydraulic cases were chosen by varying U_s and H systematically. The aspect ratio of the cross-section, B/H , was 5.0 and larger, to avoid effects of secondary currents as pointed out by Nezu and Nakagawa (1993).

Table 2 indicates hydraulic conditions for vegetated open-channel cases, in which turbulent measurements were conducted in the same way as the smooth-bed open-channel flows. The water depth H is three times greater than the vegetation height h , i.e., $H = 3h = 15$ cm. The present study deals with only submerged vegetation flow, and focuses on the relation between the vegetation density and the gas transfer velocity. A vegetation model is a 5-cm height, 0.8-cm width, 1-mm thick plastic plate that cannot warp in the water stream. They are placed vertically on the base plate with a rectangular grid form. The submerged simulated element reduces the streamwise velocity within the canopy, and it results in shear instability accompanied by coherent vortices at the vegetation top. We conducted not only surface horizontal PIV but also vertical in the $x-y$ plane. The vegetation density has been defined in the following way.

$$\lambda \equiv nhb/S \quad (1)$$

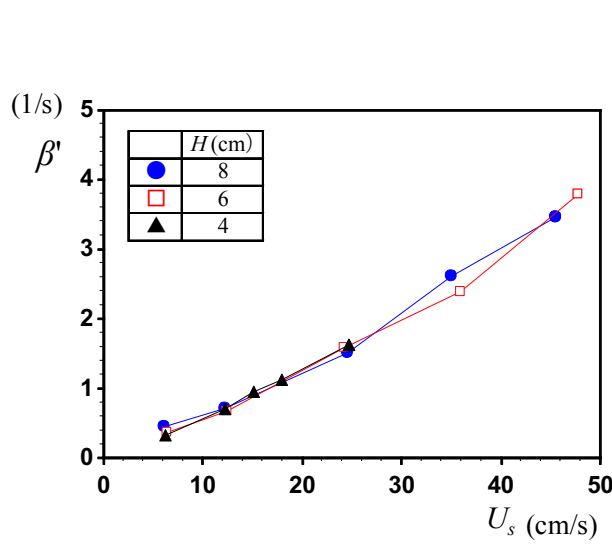


Figure 2. Relationship between surface velocity and surface divergence intensity.

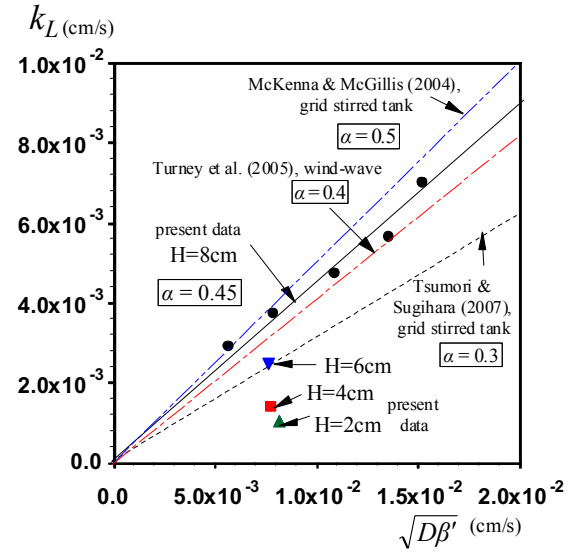


Figure 3. Examination of surface divergence model; comparison with previous measured data in grid stirred tank and wind waves.

S is the horizontal area corresponding to the vegetation zone and n is the total number of vegetation elements included in the vegetation zone. Grid span is 2.4 cm, 4.8 cm and 7 cm, corresponding to $\lambda = 0.3789, 0.0947$ and 0.0236 , respectively.

3. Results in flat-bottom open-channel flows

The surface velocity divergence at the air-water interface $\tilde{\beta}$ could be defined as the following form, in which tilde represents an instantaneous component.

$$\tilde{\beta} \equiv \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{w}}{\partial z} = -\frac{\partial \tilde{v}}{\partial y} \quad (2)$$

When $\tilde{\beta}$ is introduced instead of vertical velocity \tilde{v} , a transport equation of dissolved gas concentration is given by

$$\frac{\partial \tilde{c}}{\partial t} + \tilde{u} \frac{\partial \tilde{c}}{\partial x} + \tilde{w} \frac{\partial \tilde{c}}{\partial z} - \tilde{\beta} y \frac{\partial \tilde{c}}{\partial y} = D \frac{\partial^2 \tilde{c}}{\partial y^2} \quad (3)$$

This form implies that $\tilde{\beta}$ is an important factor when vertical gas transport is prevalent much more than longitudinal and spanwise ones. Figure 2 shows the relation between surface divergence intensity β' and the free-surface velocity or the water depth. β' is equal to RMS of the instantaneous surface velocity divergence. β' was calculated from time series of $\tilde{\beta}$ during 60 s. A fluctuation of water surface is negligibly small in the present hydraulic cases, and thus, a vertical velocity could be given by zero.

When we consider \tilde{v}_s and v'_s situated in the free surface with distance, Δy , the following relation is obtained.

$$\beta' = v'_s / \Delta y \quad (4)$$

Turbulence intensities obey universal functions proposed by Nezu and Nakagawa (1993) except for near the bottom and free-surface regions, and they could be normalized by a bottom friction velocity

U_* . There remains uncertainty about turbulence structure near the surface; when we assume $v' \propto U_*$, a proportional relation $\beta' \propto U_*$ is obtained. In the open-channel flows, U_s is proportional to U_* , and it is then expected that β' is proportional to U_s . This tendency is observed in figure 2. A variation of β' is relatively small against the water depth.

In a surface renewal model (SR model), k_L is given by

$$k_L \propto \sqrt{Dr} \quad (5)$$

in which D is molecular diffusivity of dissolved oxygen in water and r is a surface renewal rate. Physical gas transfer modeling has been generally conducted on the basis of equation (5).

In contrast, McCready *et al.* (1986) proposed a surface divergence model (SD model) by connecting the gas transfer velocity and the surface velocity divergence.

$$k_L = \alpha \sqrt{D\beta'} \quad (6)$$

in which α is a proportional coefficient. The validity of the SD model was examined mainly for the grid-stirred tank experiments. However, not much is known about open-channel flows.

Figure 3 shows the relation between k_L and β' , in which measured data in the grid-stirred tank and wind-induced water waves are indicated for the comparison. When the water depth is fixed, there is a linear relation in the present data as well as previous studies. α varies in a range of 0.3 to 0.5 in previous studies, and it is 0.45 in the present study of $H = 8$ cm. Therefore, the present proportional coefficient agrees well with those observed in other kinds of flow fields.

The linear relation is not observed among different water depth cases. Thus, a more practical SD model should be proposed for the open-channel cases such as natural rivers.

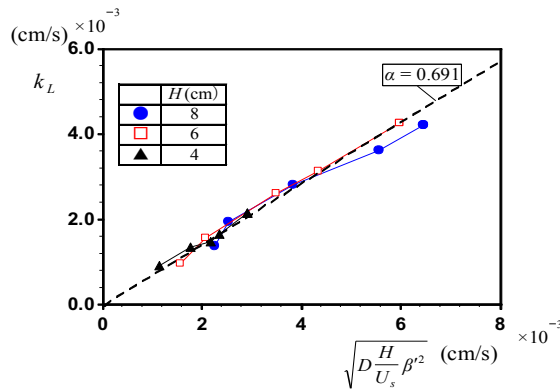


Figure 4. Relationship between gas transfer velocity and $\sqrt{DH\beta'^2/U_s}$

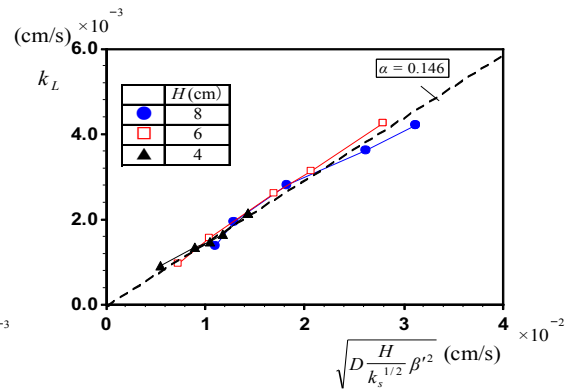


Figure 5. Relationship between gas transfer velocity and $\sqrt{DH\beta'^2/k_s^{1/2}}$

The proportional coefficient α in the original SD depends on the water depth. In a new proposed model, the water depth is chosen as characteristic length scale. It is further important in modeling of surface renewal rate to select only hydrodynamic values obtained by horizontal PIV measurements in field measurements in terms of practical use. When the surface streamwise velocity U_s is chosen as characteristic velocity, the new transfer model is indicated in the following way.

$$k_L \propto \sqrt{D \frac{H}{U_s} \beta'^2} \quad (7)$$

Figure 4 shows variation of the gas transfer velocity against $\sqrt{D\beta'^2 H/U_s}$. The linear relation could not be obtained with little dispersion, irrespective of the water depth.

The surface renewal process is correlated to the coherence turbulence, and thus, the turbulence statistics such as turbulent kinetic energy, turbulence intensity, and eddy advection velocity, etc., may be better for the characteristic velocity scale than the time-averaged velocity such as U_s . When we assume that vertical turbulence intensity at the free surface is ignorably small compared to streamwise and spanwise ones, the turbulent kinetic energy of the free surface k_s could be indicated by

$$k_s^{1/2} \equiv \frac{1}{2}(u'^2 + w'^2) \quad (8)$$

When k_s is used for U_s , the following relation could be introduced.

$$k_L \propto \sqrt{D \frac{H}{k_s^{1/2}} \beta'^2} \quad (9)$$

Figure 5 shows variation of the gas transfer velocity against $\sqrt{D\beta'^2 H / k_s^{1/2}}$, in which a linear relation is recognized. The standard deviation of $k_L / \sqrt{D\beta'^2 H / U_s}$ is greater than $k_L / \sqrt{D\beta'^2 H / k_s^{1/2}}$. This suggests that equation (9) is more reliable than equation (7). Then, equation (10) could be proposed for an experimental formula about gas transfer velocity in open-channel flows.

$$k_L / \sqrt{D \frac{H}{k_s^{1/2}} \beta'^2} = 0.146 \quad (10)$$

In the near future, we will examine equation (10) in a larger scale laboratory flume and natural rivers.

4. Gas transfer in vegetated-bottom conditions

Figure 6 shows the relation between the surface divergence intensity and the vegetation density. This result suggests that the divergence intensity increases with increased vegetation density. This may be because the large-scale coherent vortex plays a more significant role on the surface renewal in the denser vegetation case. Some previous studies offered that more remarkable shear instability could be observed in the denser vegetation, and corresponding integral scales of coherent structure increase significantly.

Figure 7 and figure 8 show significant relations of k_L and $\sqrt{DH\beta'^2 / U_s}$, and k_L and $\sqrt{DH\beta'^2 / k_s^{1/2}}$, respectively. In figure 7, the results of the non-vegetation case, i.e., only a base plate over the flume bed, agree with the linear relation of equation 6, while those in the vegetation cases shift below smooth bed results. This implies that U_s cannot be used as the velocity scale to consider large-scale turbulence induced by the coherent vortices near the vegetation top.

In figure 8, the results of vegetation cases are consistent with equation 10, irrespective of the vegetation density. This suggests that the prediction model using turbulent kinetic energy as the velocity scale has a wide generality.

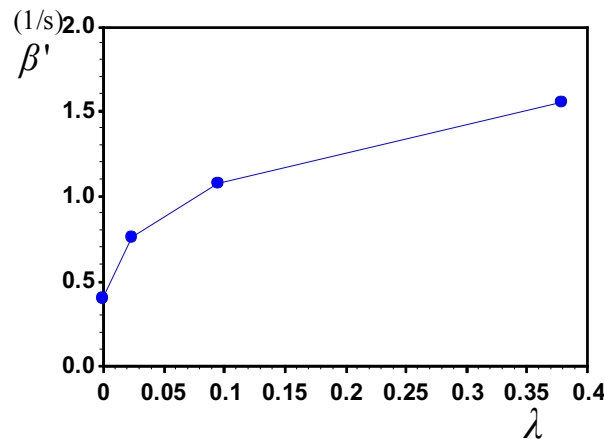


Figure 6. Relation of surface divergence intensity and vegetation density.

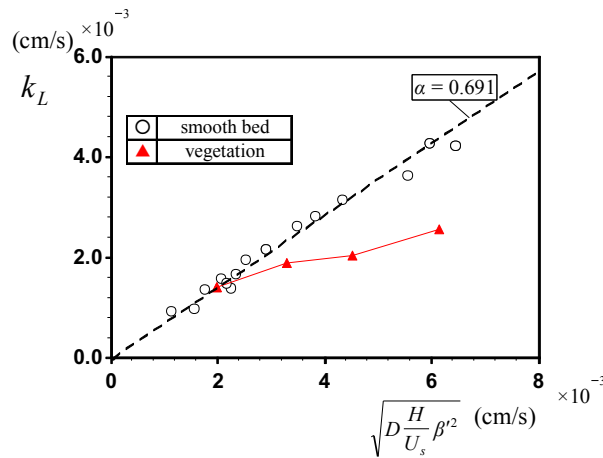


Figure 7. Relation between gas transfer velocity and $\sqrt{DH\beta'^2/U_s}$ for both bottom types.

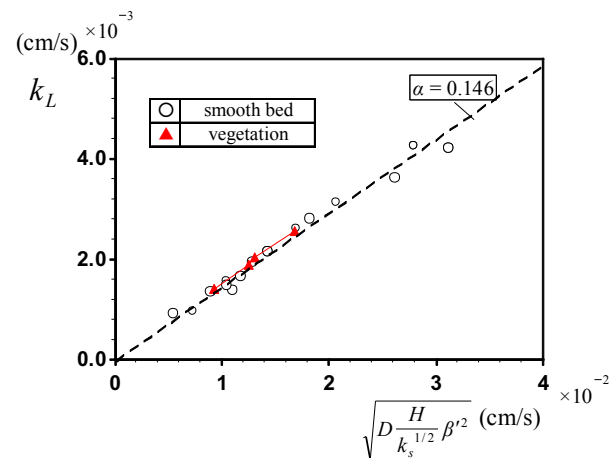


Figure 8. Relation between transfer velocity and $\sqrt{DH\beta'^2/k_s^{1/2}}$ for both bottom types.

5. Conclusions

It was found that a proportionality coefficient of the original SD model depends on the water depth. The present study developed a modified SD model that considers the effects of water depth on gas transfer. We examined whether the free-surface streamwise velocity and turbulent kinetic energy are used as a proper velocity scale, and then, in both cases, the modified SD model is useful without a dependency on the bulk-mean velocity and the water depth in flat bottom conditions.

When the modified SD model using the free-surface velocity is applied to the vegetated open-channel flows, there is a large gap between the smooth bed case and the vegetated. In contrast, the modified model using the turbulent kinetic energy has a constant proportionality coefficient, irrespective of bottom roughness conditions. It is therefore indicated that the modified SD model, which gives the surface renewal rate using the turbulent kinetic energy and surface divergence, has the same proportionality coefficients for smooth and vegetated bottoms.

References

- [1] McCready M J *et al* 1986 *AIChE J.* **32** 1108
- [2] Nezu I and Sanjou M 2011 *J. Hydro-environment Res.* **5** 215
- [3] Moog D B and Jirka G H 1999 *J. Hydraulic Eng.* **125** 3
- [4] Nezu I and Nakagawa H 1993 *Turbulence in Open-Channel Flows* (CRC Press)
- [5] Komori S *et al* 1989 *J. Fluid Mech.* **203** 103